HUDDLESTON

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DIAGNOSTIC SIGNIFICANCE OF MACRO- AND MICROSCOPIC FEATURES OF CATASTROPHIC GUN-TUBE FAILURES

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(10) MR. ROBERT L. HUDDLESTON
MATERIEL TESTING DIRECTORATE
ABERDEEN PROVING GROUND, MD. 21005

Failures of weapons and ammunition under test at Aberdeen Proving Ground have provided our laboratories with a unique opportunity to examine material reactions to explosive loading. Physical and metallurgical findings for 22 weapon and ammunition prematures have recently been summarized (1). Of these prematures, 6 were accidental and the remainder deliberately induced to better study our problem. An on-going methodology effort is required to improve the means of determining the cause of weapon failures. It will not be possible to cover this 10-year effort in detail; rather, I shall explain the problem and approach in general terms, point out some of the details which have been observed, and summarize the state-of-the-art.

The first question is always "What caused the failure?" This question leads to others, less difficult to answer, such as "Is the gun tube or the ammunition at fault?" or, if a high-explosive (HE) shell is involved, "Is this a high- or low-order detonation?" or, "What was the direction of propagation of the explosive force?" Our metallurgists provide information to answer these questions.

It is believed by many investigators that the intensity of the explosion is the clue to the probable cause of a premature of a fuzed, HE-filled round. This is based on the opinion that a true high-intensity (high-order) detonation is not likely to be produced by other than proper functioning of the fuze and the entire explosive train. Most investigators, in classifying the order of functioning, have described prematures as low-order or high-order, without regard to the possibility of events on an intermediate scale of intensity.

For convenience, we have designated as high-order only those prematures that appear to function with the full detonation intensity. Those of a lower order of intensity have been classified as low-order, although they appear to lie at intermediate levels between full detonation and low-order deflagration.

Almost all metallurgists engage in the analysis of metal failures at some time. The methods for such analyses are well standardized, and such methods are useful for examination and analysis of weapon failures; however, additional observations are specifically associated with the results of exploding shell. Information concerning the events and conditions surrounding the failure must be considered, as well as data that can be obtained after the fact by a variety of destructive and nondestructive tests. Once the test conditions (such as rate-of-loading, environmental, and other possible variables) have been identified, the overall appearance of the failed material is considered.

MACROSTRUCTURE

It is important to examine metal fracture surfaces before rapid corrosion sets in to conceal vital indications on the fresh, highly energetic surface. Fracture tracing can be done on mixed-mode fracture surfaces that reveal a "herringbone" or "chevron" pattern, indicating the direction of crack propagation. The chevron "V's point toward the direction of propagation when the fragments are reassembled, in jigsaw fashion.

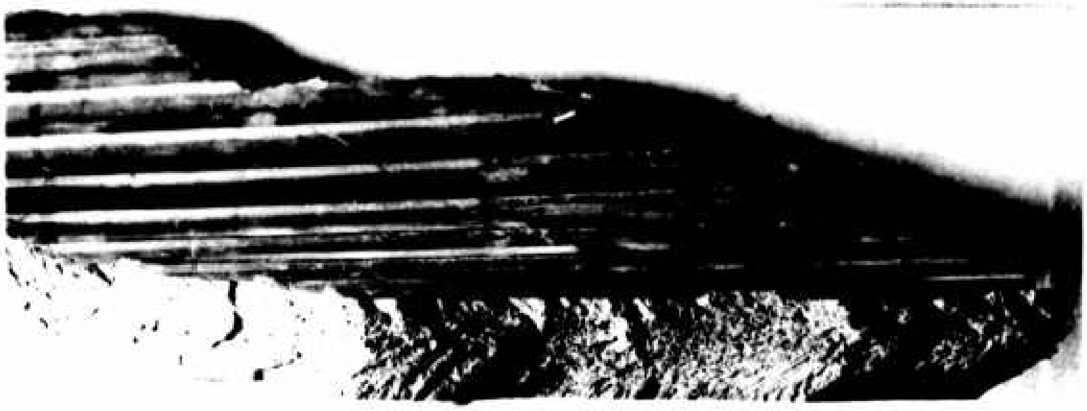


FIG. 1 Chevron Fracture (1X)

Unfortunately for the examiner of weapon prematures involving detonating HE, there is a fracture phenomenon that limits the fractographer tracing the fracture to an area near (but not at) the point of initiation.

Steels show a transition from ductile to brittle behavior as the rate of loading increases from a static to a more dynamic rate; however, the alloy steels used in cannon show another reversion to a ductile mode of failure at explosive loading rates. Thus, the chevron pattern that appears on fracture surfaces in dynamically loaded areas away from the immediate detonation zone disappears as the detonation zone is reached; the failure mode is usually massive slant shear. A brittle fracture mode in the detonation zone may indicate less than high-order of HE function.

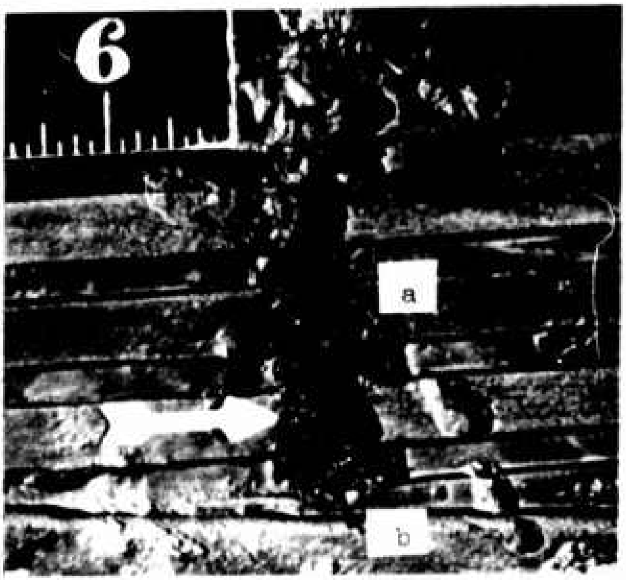
The fragment size for both tube and projectile are significant. Smaller sizes indicate higher orders of explosive functioning. The symmetry of the fracture pattern is also significant. Central initiation (such as from the fuze) will produce a symmetrical pattern.

Part of the macroscopic examination involves recording the "signature" of the exploding round in the tube. These markings are caused by fragment impacts, shock pulses, and hot gases, with the pattern of indentations in the tube being shaped by the geometry of the interacting parts. Like the fracture surfaces, these indicator areas must be examined at the earliest possible moment before oxidation and other forms of corrosion change the appearance.

The location of the projectile rotating band in the tube at the time of detonation is sometimes indicated by a brassy "glint" in the form of a circumferential band around the bore surface. Depending upon the force of detonation, a ring of indentations may be formed at the location of sharp corners at the edge of the steel shell body and the rotating band. In some instances, the soft metal of the band serves to protect the bore area underneath, and results in less flattening of the bands than occurs where the steel shell body contacts the bore surface.

FIG. 2 Unflattened Land at Band (1X)

HE shell of several types have been shown to produce a circumferential ring of pits or fragment indentations corresponding to the ogive area of the shell. These pits increase the depth as the nose of the shell is approached. Apparently, the shell body, which is in close contact with the bore, does not fragment as does the



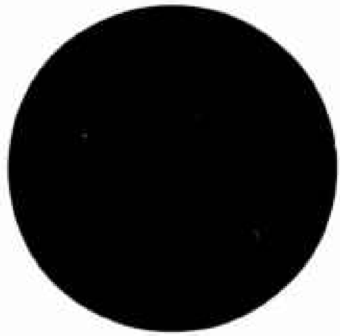


FIG. 3 Fragment Ring

unsupported ogive, fragments of which are projected into the tube at an angle, as driven by the expanding gases. HE antitank rounds (HEAT) produce an especially distinct nose fragment ring when they function in-bore.

Spallation of the tube wall may indicate high-order functioning. In thick-walled tubes, however, the absence of such spallation does not preclude a high-order. This will be further discussed under "Microstructure."

Tube fragments from a high-order detonation area have shown a transfer of tool marks from the outside surface of the shell body to the tube bore surface. Recovered shell fragments usually show rifling engraving, with higher orders of functioning showing deep engraving. Flattening of lands is always noted with high-order functioning. Recovered shell-body fragments may show pitting on the inner surface, caused by "jetting" of HE during high-order detonation.

Fragments of the tube must be examined for evidence of prior fatigue cracks. An experiment was performed at APG by machining a critical-sized slot in a cannon tube and firing HE shell. The tube fractured on the second round but the projectile cleared the tube and did not detonate in-bore. Still, the possibility of such a cause for a premature cannot be ruled out. Prior fatigue cracks are usually

evidenced by a stained or discolored surface or a mismatched mode (fatigue beach marks on a flat radial crack surface with chevrons radiating outward).

MICROSTRUCTURE

It is the usual practice to remove sections from the origin of failure (or the detonation zone) and also from a location distant from the detonation zone for a comparison of microstructure. The pressure, high surface temperatures, and erosive effects of the detonation products create a number of microstructural changes that can help in the analysis of the failure.

One of the more striking features produced by any order of detonation with sufficient force to rupture a tube is the martensitic streaks, which have been described as being caused by adiabatic shear (2). These indicate the presence of intense shear loading but,

FIG. 4 Adiabatic Shear (500X)

unfortunately, cannot be used to distinguish between high- and low-order detonations since they occur for both conditions. It has been thought that the direction of these "streaks" could be related to the direction of principal stress propagation, but to date they have not proved to be useful for this purpose During the breakup of a gun tube in the presence of an explosion, the shocks and reflections appear to form a virtual "tangle" and the direction of any given shear line and the direction of main stress propagation appear to be unrelated. Further observations are needed to better determine the usefulness of this observed phenomenon.

Microsections from the detonation zone, showing an increase in the number of microvoids or microcracks, are considered to be evidence of shock loading from a high-order detonation. These microvoids join to form the cracks, which result in spallation of the tube wall. Their absence does not, however, rule out the possibility of a high-order function in a thick-walled gun tube. The interference between the tail of the incident and the reflected shock wave produces the tensile stress that opens the first voids. This stress may not be of sufficient intensity in the case of a thick-walled tube.

Another unusual condition has been noted on the surface of both tube and projectile fragments from in-bore prematures. A duplex white layer has been observed; this resembles the white layer seen by many examiners of worn gun tubes, believed to result from heat and the nitrogen from the propellent gases. One reference (3) reports the observation of three distinct zones: a) a subsurface tempered zone, softer than the underlying steel; b) a rehardened light etching, nearer the surface area; and c) a darker etching platelet containing layer at the surface. We have observed similar layers on tube and shell fragments and, at least in the case of the shell, the transformations resulted from the single explosion, not a large number of rounds fired over a period of time. Such transformed surface layers

FIG. 5 Layers on Shell (100X)

have not been observed on recovered shell that were fired under normal conditions and apparently are caused by the intense heat, possibly in combination with the pressure of the detonation gases. Almost all fracture surfaces of tube and shell fragments exhibit a gas-washed surface layer. This alteration of fracture surfaces, by masking

fracture detail, has seriously impeded efforts to better analyze fracture surfaces with the scanning electron microscope. The diagnostic significance of this observation is that the presence of a "white layer" in surface cracks in tube fragments after detonation is not necessarily evidence of a pre-existing fatigue crack, as has been believed by some investigators.

FIG. 6 White Layer in Shear Crack (Top 8X, Bottom 250X)

Another aspect of gas effects on fragment surfaces is the depositing of traces of different metals found in the projectile. Copper and aluminum have been found on every fracture surface of tube fragments from HEAT-round prematures, when examined by X-ray spectrographic analysis. In one instance, it was wrongly concluded that the presence of copper on a fracture surface was evidence of a pre-existing fatigue crack, into which copper from a gilding-metal rotating band had been squeezed during earlier firing schedules.

MECHANICAL

Changes in the mechanical properties have been observed in shell and tube fragments, and attempts have been made to relate these to the direction of propagation and order of function, by investigators at Picatinny Arsenal (4) and the Naval Weapons Laboratories (5), as well as at APG. The greater changes usually occur to projectile parts (which, unfortunately, are often not recovered from field prematures). Although some investigators have related the changes in hardness profile to the direction of propagation, the results of the APG investigations have not shown this to be a consistent indicator; however, the amount of hardness change in tube fragments has been shown to be an indicator of order of function. High-order functions cause an increase in Rockwell "C" hardness of 4 points or more in detonation-area fragments. Lower-intensity functions cause a lesser increase. Tensile tests have revealed a similar increase in yield strength in fragments from both high- and low-order functions, however, for functions classed as "low-order", the increase is slight.

A summary of the characteristics of high- and low-order prematures follows. This determination, in conjunction with fractographic tracing and other signature interpretation, can suggest the cause of failure. The evidences of function order include:

a. High order:

(1) Always noted:

(a) Land flattening
(b) Tube well fragmented
(c) Land engraving on all projectile fragments
(d) Significant increases in tube-and-projectile hardness

(2) Usually noted:

(a) Tube spallation (microcracks and voids)
(b) Pitting on ID surface of projectile fragments

b. Noted on both high and low order:

(1) Adiabatic shear

(2) Thinning of projectile wall

(3) Slight increase in tube and projectile hardness and yield strength

(4) Gas-wash on fragment surfaces (transformed layer)

(5) Fragment ring in tube at projectile nose.

Plans for further work on techniques for analyzing permatures will take into account work done at the Naval Weapons Laboratories with computer simulation using a HEMP code (6). Very briefly, conventional projectile signature examination was used to determine the location of the prematured projectile in the gun tube. A HEMP program was then adapted to simulate a fracture of the tube for both nose- and base-initiation of the HE filler. The event that best matched the physical condition of the tube after actual detonation was chosen as the solution to the problem. In three actual instances, a nose-initiation was found to be the source of the detonation. We have proposed further work to prove the correctness of this approach, involving a comparison of the computer simulation results with an induced premature under the most carefully controlled conditions.

CONCLUSIONS

It is concluded that:

a. Metallurgical analysis can provide information useful for determination of the cause of accidental in-bore prematures by:

(1) Determining the exact location of the shell at detonation time.

(2) Determining the order of functioning.

(3) Determining the direction of explosive propagation.

(4) Identifying the tube or ammunition as the cause of failure.

b. Computer simulation should be considered in future studies as a possibly more economical means of simulation than by actual induced in-bore prematures.

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